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OVERVIEW OF NASP NOZZLE RESEARCH

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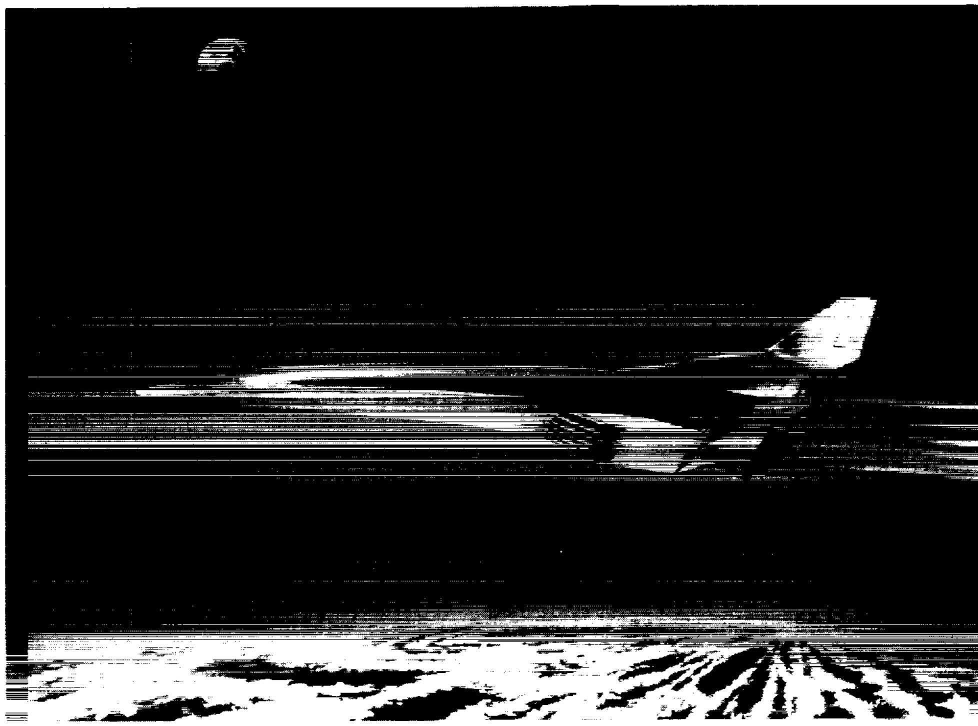
Problems facing the National Aerospace Plane (NASP) nozzle at transonic and low supersonic conditions are discussed. An overview of NASP nozzle research at Lewis Research Center is given. Experimental facilities and computational techniques currently in use are reviewed. External burning as a means to reduce transonic drag and initial results of external burning experiments are discussed.

Aerospace Vehicle Employing Highly-Integrated Exhaust Nozzle



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Interest in transatmospheric or aerospace vehicles has been revived in the United States following almost two decades of relative inactivity. Evolutionary advances in scramjet propulsion, materials, and computer modeling have set the stage for an aggressive program (the National Aerospace Plane, or NASP) to develop a revolutionary aircraft capable of flying into orbit following takeoff from a conventional runway. Ready access to space, and very high speed Earth transportation are but two of the obvious benefits of this technology. A single stage to orbit concept is very attractive due to its operational simplicity, flexibility and its potential for reducing the cost of putting payload into orbit. The technical challenges facing the aerospace community are numerous, many of them related to the airbreathing propulsion system required to achieve orbit in a single stage. Liquid hydrogen fuel is widely accepted as the fuel of choice for hypersonic airbreathing propulsion due to its high heat capacity for engine and airframe cooling, and a heat of combustion twice that of hydrocarbon fuels. One drawback of hydrogen is its low molecular weight which results in a large cryogenic volume that must be highly integrated with the airframe and propulsion system. An artist's conception of the National Aerospace Plane appears in this figure to illustrate a typical highly integrated configuration with a large, scarfed, two-dimensional exhaust nozzle. The entire vehicle aft end acts as an expansion surface for the scarfed nozzle, providing a very high area ratio which is exploited at the high nozzle pressure ratios associated with high Mach number and altitude. This large aft-facing area becomes a critical issue, however, at transonic and supersonic speeds where relatively low airbreathing engine pressure ratios result in a highly overexpanded nozzle.

At Low Speed, the NASP Nozzle Is Highly Overexpanded

- **Determine nozzle operating characteristics from takeoff to moderate supersonic speed**
- **Develop drag-reduction techniques, specifically external burning**

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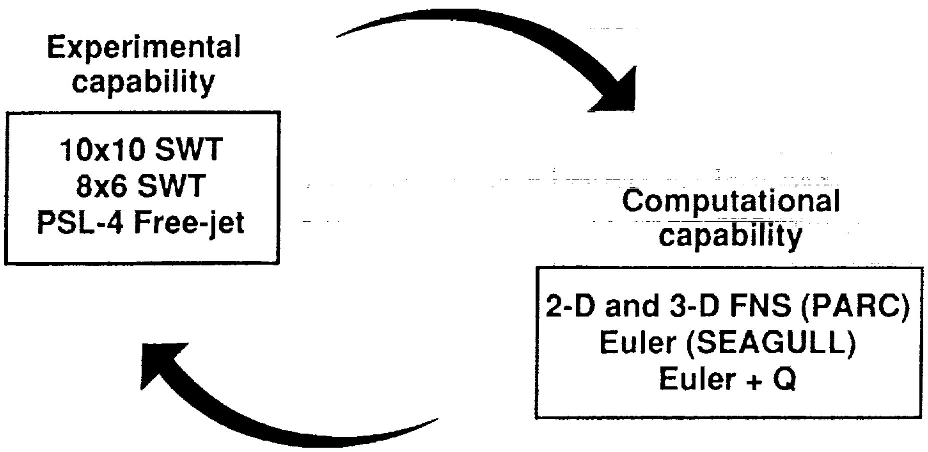
The design of a nozzle required to operate from takeoff to orbit is a formidable task. The amount of variable geometry that can be employed is a small fraction of that required to keep a nozzle "on-design" over this speed range, mainly because of the invariability of the vehicle aft end which must be used as the nozzle expansion surface.

A primary goal of NASP nozzle studies at the NASA Lewis Research Center is to determine the performance characteristics from low to moderate supersonic speeds for the candidate configurations. The poor performance resulting from off-design operation necessitates some form of augmentation especially at transonic speeds. External burning has been studied at Lewis as a potentially attractive solution.

Approach



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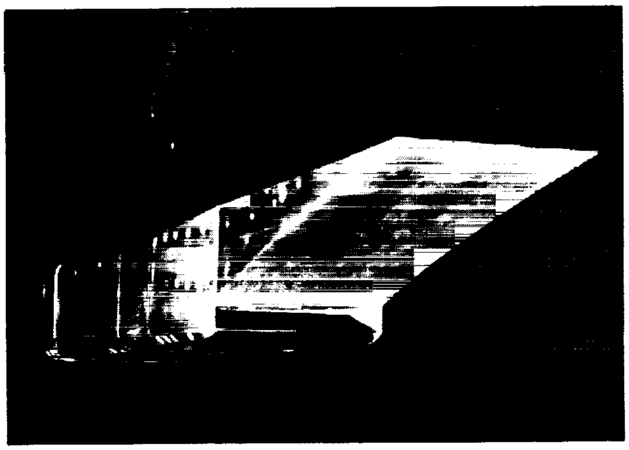
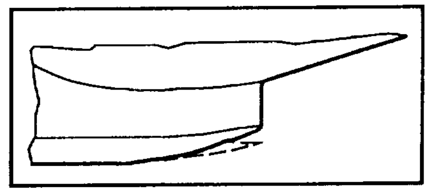
Nozzle research at Lewis encompasses a wide range of both experimental and computational activities. Recently, a heavier emphasis has been placed on building an hierarchy of numerical capability for performance prediction, wind tunnel model design, and experimental data analysis. Computer codes currently in use vary in sophistication from two-dimensional Euler analysis, such as SEAGULL, to three-dimensional Full Navier-Stokes (FNS) solvers, such as PARC. Experimentally, Lewis is using the 10- by 10-Foot and 8- by 6-Foot Supersonic Wind Tunnels (SWT's) as well as a number of smaller facilities such as a Mach-1.26 free-jet in cell 4 of the Propulsion Systems Lab (PSL-4).

NASP Jet-Effects Test Rig
Lewis 10x10 SWT

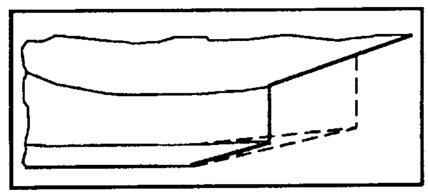
Installed in Lewis 10x10 SWT



Geometry Variations



Internal Area Ratio



Extended Cowl

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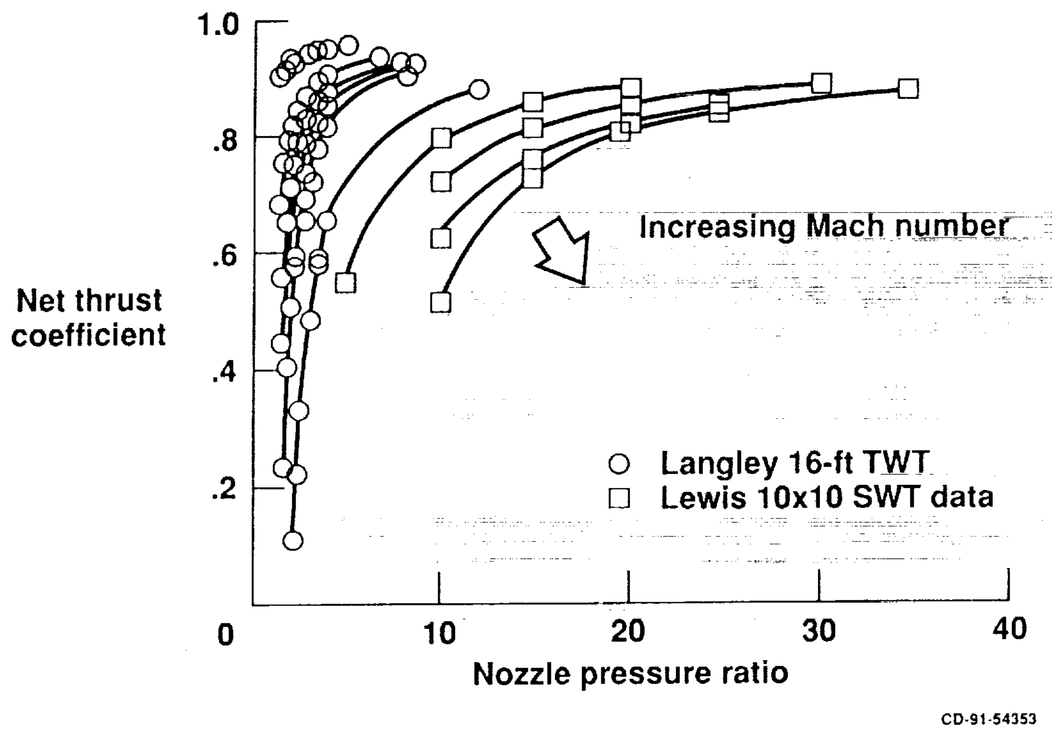
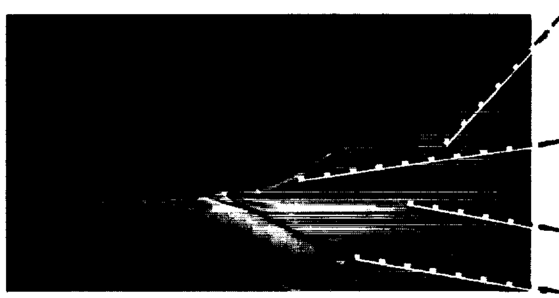
The primary purpose of this test was to determine the low-speed (Mach 2.0 to 3.5) performance of generic nozzle/afterbody configurations designed for a hypersonic propulsion system. This test was an extension of transonic tests conducted at the NASA Langley 16-Foot Transonic Wind Tunnel. The objectives of these tests were to determine nozzle afterbody thrust-minus-drag levels and vector angle, define separated flow regions on the afterbody with and without sidewalls, determine the influence of afterbody shape and length on performance, determine the effect of upstream contour on performance, provide an experimental database for computational fluid dynamics calibration, and determine throttle-dependent changes on afterbody forces. The data obtained from these series of tests establishes an experimental database for this class of nozzle/afterbody configurations and will be used to guide NASP propulsion/airframe design and integration.

NASP Low-Speed Database Extended to Mach 3.5

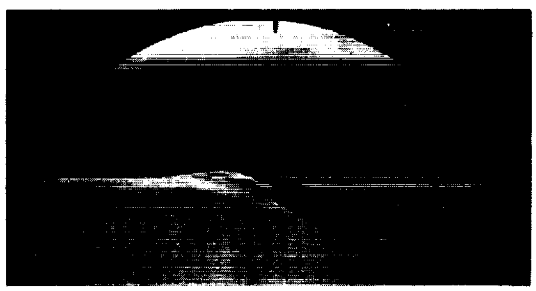


This is a plot of net thrust coefficient versus nozzle pressure ratio for the baseline nozzle/afterbody configuration. Transonic data (Mach 0 to 1.2) was obtained in the NASA Langley 16-Foot Transonic Wind Tunnel. Supersonic data (Mach 2 to 3.5) was obtained in the Lewis 10- by 10-Foot Supersonic Wind Tunnel. The net thrust shows an expected increase with nozzle pressure ratio, and the peak nozzle performance shifts toward higher nozzle pressure ratios as the Mach number increases. In general, the nozzle pressure ratio available in current NASP engine cycles is less than the peak value, necessitating thrust augmentation at low Mach numbers.

Schlieren Images Aid Understanding of Overexpanded Nozzle Flow Fields



Low Nozzle Pressure Ratio



High Nozzle Pressure Ratio

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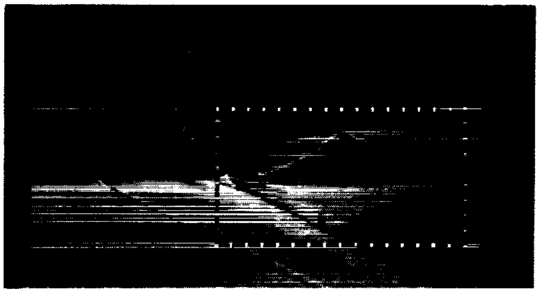
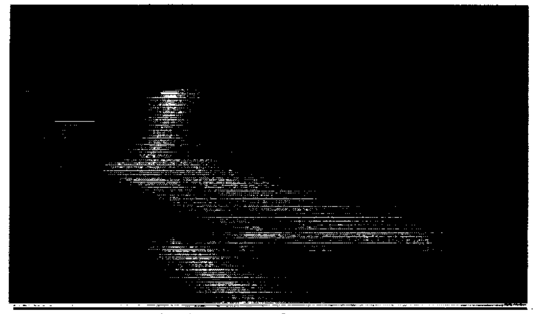
Schlieren flow visualization techniques were used to qualitatively evaluate the flowfields generated by an overexpanded nozzle in the Lewis 10- by 10-Foot Supersonic Wind Tunnel. The upper schlieren image shows an internal shock wave being generated by the nozzle/afterbody that intersects the nozzle ramp surface and causes the boundary layer to separate for a low nozzle pressure ratio, overexpanded flow condition. This phenomena is contrasted by the lower schlieren figure, which shows an external shock wave and shows the shear layer generated from the interactions of the nozzle plume and tunnel flow at a high nozzle pressure ratio, underexpanded flow condition. For this flow condition, the nozzle flows full without the boundary-layer separation caused by an internal shock wave, as in the underexpanded flow case.

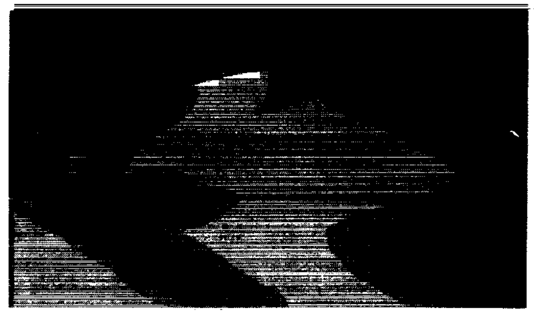
Computational Capability for Overexpanded Hypersonic Nozzles



Schlieren Photo



2-D Euler Solution



3-D Euler Solution

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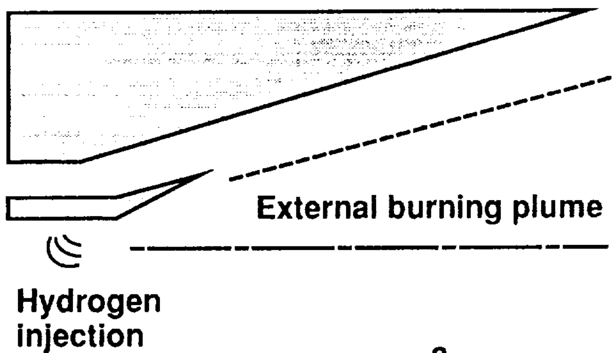
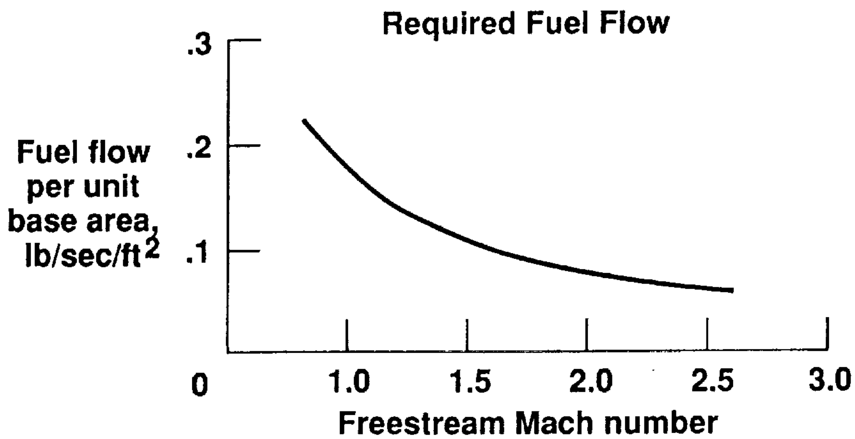
Computational analysis is necessary to predict and understand the behavior of the complex flowfields of hypersonic nozzles. Analytical models can provide insight into the characteristics of these flowfields, and they can also help predict performance of certain configurations - thus saving the cost associated with experimental testing. One way of comparing analytical data with experimental data is a density contour plot. Density levels can be qualitatively compared with schlieren photographs. On the left is a schlieren photograph taken of one configuration tested in the Lewis 10- by 10-Foot Supersonic Wind Tunnel. Here, the nozzle was operating at a pressure ratio of 15 in a Mach-2.5 free stream. Two computer analyses were used to model the same geometry, in an effort to predict the locations of the external shock, the shear layer, and the shock deflecting off the ramp surface - all seen clearly in the schlieren image. The top right figure shows results from SEAGULL, a two-dimensional Euler analysis. SEAGULL uses shock-fitting, a technique that calculates shock locations on the basis of discontinuities in pressure or geometry. The bottom right figure shows results from a PARC3D, three-dimensional Euler analysis. Both figures show favorable results in predicting the shear layer and shock locations.

External Burning to Reduce Transonic Drag



- Proof-of-concept experiments
- Control-volume analysis
- Euler analysis



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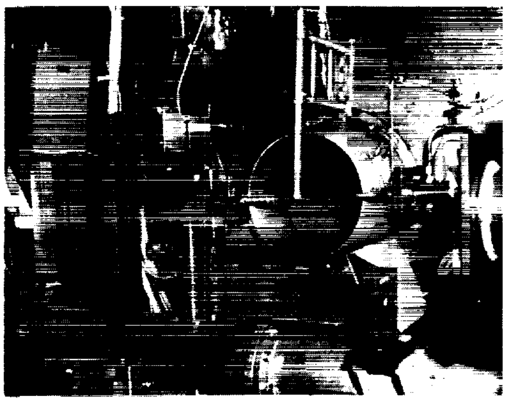
A conceptually attractive solution to the transonic nozzle drag problem is the combustion of fuel in an external stream of air passing adjacent to the cowl. If the burning streamtube could be made to expand at free-stream pressure, then the drag on the cowl flap would be eliminated, and the exhaust flow would exit to ambient pressure without overexpanding. This concept was studied by using a control-volume approach to estimate the performance potential and fuel flow requirements. The fuel flow required to eliminate drag along a 1000-psfa dynamic pressure trajectory is shown. The roughly 0.1- to 0.2-lb/sec/ft^2 of base area gave high specific impulse performance and warranted further study.

External Burning Flame Stability Experiment Helps Define Operational Limits

Spraybar Installed in PSL-4 Free-Jet



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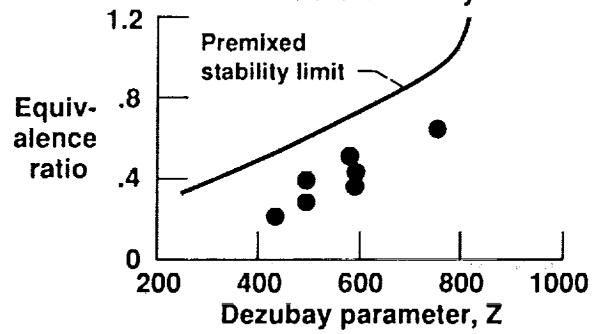
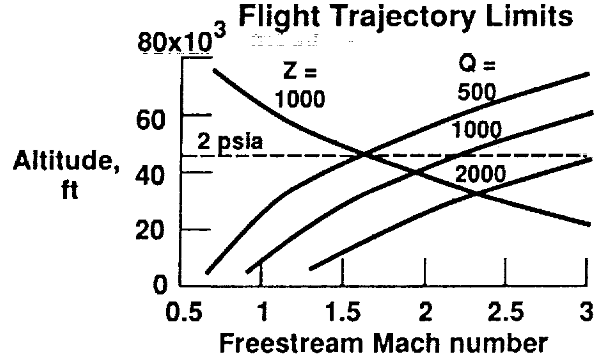
PSL-4 Basic Stability Data



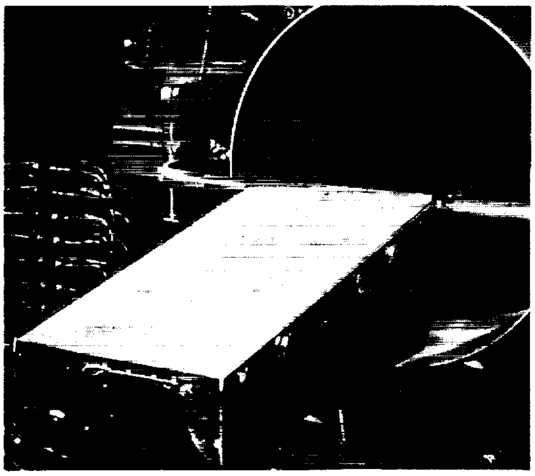
Flight Trajectory Limits

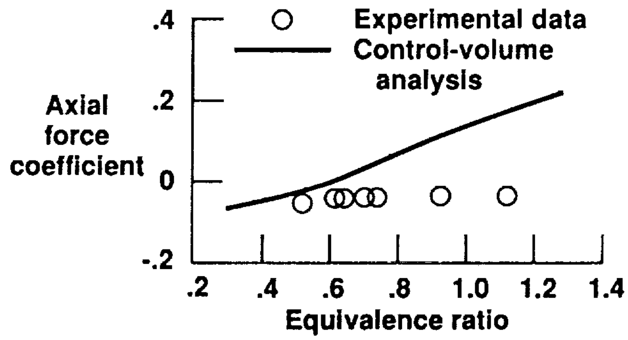


To determine combustion stability limits for a non-premixed stream of hydrogen and air, a spraybar test was conducted in a Mach-1.26 free-jet at Lewis. The photograph on the left shows the spraybar model mounted in the free-jet with a translating spark ignitor extended from above for ignition. Flame stability data were obtained and appear on the upper right plot where equivalence ratio is plotted versus the Dezubay flame stability parameter. The premixed stability limit determined experimentally by Dezubay is also shown. A Dezubay parameter value of about 1000 may be construed as a practical limit from this figure. An altitude versus Mach number chart appears in the lower right on which three trajectories are plotted along with the Dezubay limit of 1000 (for a 1-in. high flameholder). The 2-psia limit is also shown beyond which stable combustion is unlikely no matter what size flameholder is employed. It appears from this preliminary study that external burning is operable to low supersonic Mach numbers with lower altitude trajectories being stable over a wider range.

External Burning Drag-Reduction Experiment
Lewis PSL-4

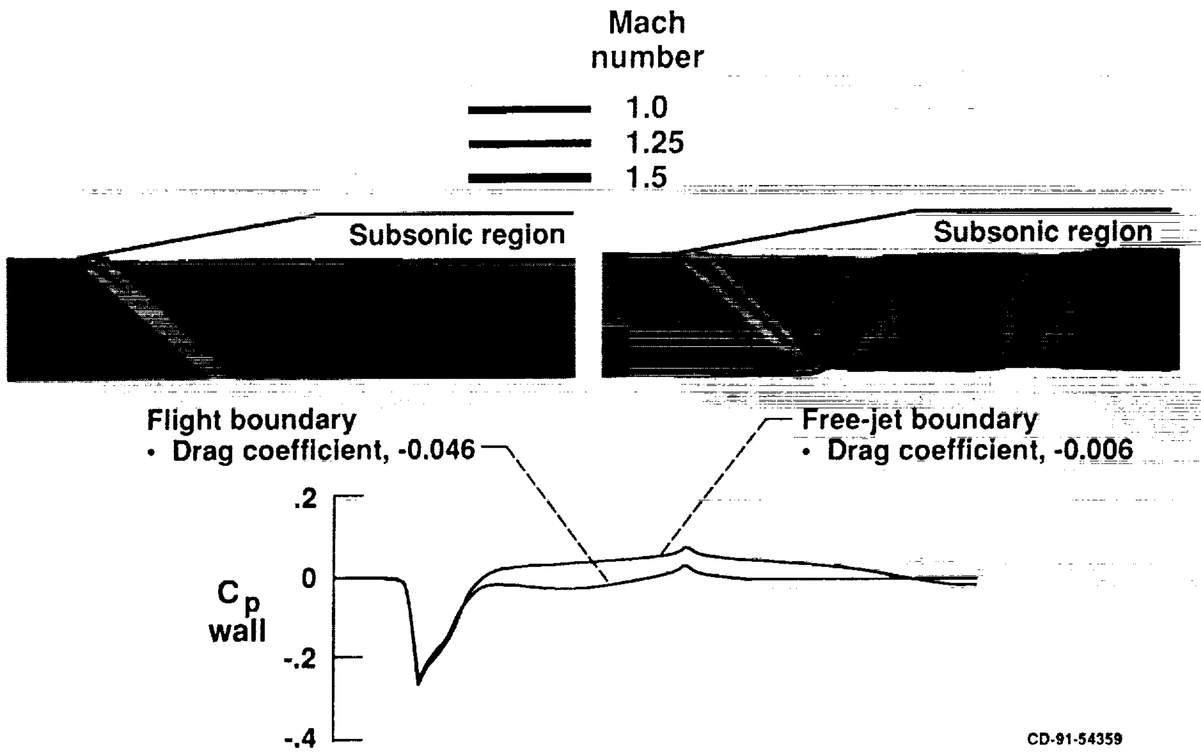
Model Mounted in Mach-1.26 Free-Jet





The expansion ramp tests were intended to demonstrate drag reduction on a generic expansion ramp geometry, while providing calibration and verification information for analysis methods. No changes were made to the facility, and the expansion ramp models were mounted in the free-jet in much the same way as the spraybar models. The basic configuration, which is shown in the photograph, consisted of a 3- by 6-in. flat plate with a sharp leading edge, followed by an 11.2-in. long, 12° expansion ramp. Fuel was injected through a row of sonic orifices that were 1/2-in. upstream of the start of the expansion. A 1/8-in. high flameholder was employed to anchor the flame at the expansion. The model was tested over a range of fuel pressures and altitudes resulting in equivalence ratios from about 0.5 to 1.2. On the right is a plot of thrust coefficient (obtained by pressure-area integration) versus equivalence ratio which shows that performance is somewhat less than predicted by the control volume analysis. This performance decrement is the subject of current investigations and is attributed to poor combustion efficiency and to interactions of the free-jet boundary with the external burning plume.

Euler Analysis Used to Assess Free-Jet Boundary Interaction



A two-dimensional Euler analysis with heat addition (Euler + Q) was used to assess the magnitude of the free-jet interactions. Multiple wave reflections between the free-jet boundary and the external burning plume can be seen in the Mach number contour plots. The net result of this interaction is to lower the magnitude of the axial force over the entire range of equivalence ratios. As can be seen in the pressure coefficient plot for a low equivalence ratio case, the free-jet boundary interaction results in higher pressures and increases performance. The opposite is true for cases where thrust is generated.

NASP Jet–Exit Rig Further Extends Low–Speed Database

- Hydrogen-air combustor simulates ramjet exhaust
- External burning capability

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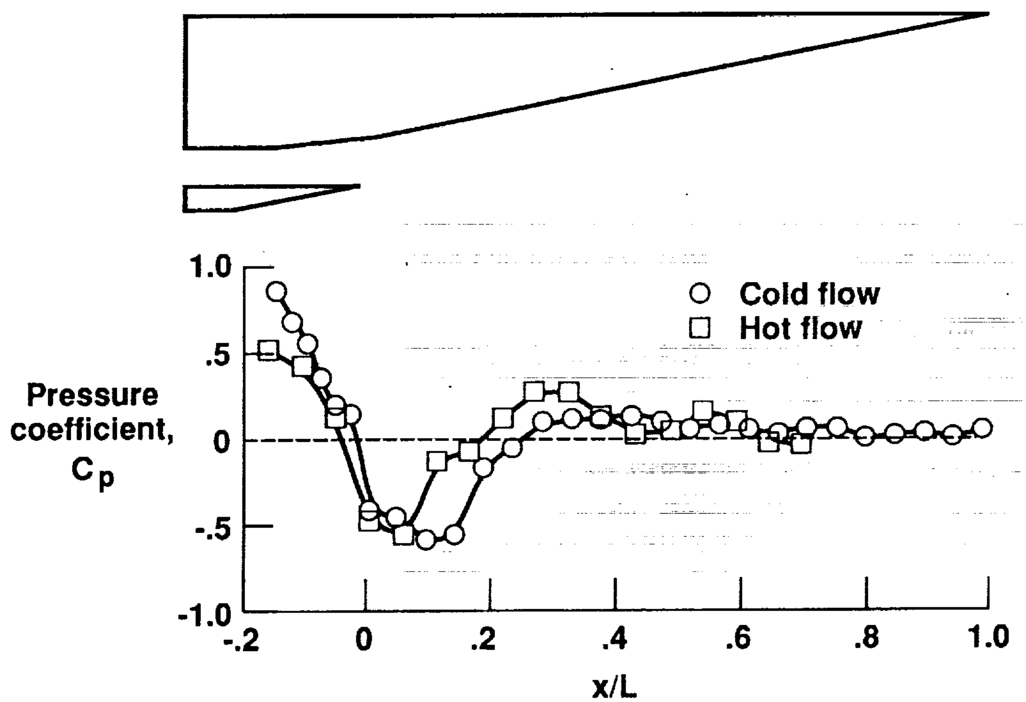
This photograph shows the newly designed and fabricated jet exit rig installed in the Lewis 8- by 6-Foot Supersonic Wind Tunnel. This rig will be used to perform tests on nozzles of various geometries. It contains a hydrogen-air combustor, a six-component force balance, and an internal flow measurement system. The first use of this test rig will be in support of the NASP program to extend the low-speed nozzle/afterbody performance database with hot flow data. The hydrogen-air combustor can provide temperatures up to 4500 °R, but will be used to supply ramjet exhaust flow up to 3500 °R for this test. In addition, the use of external burning as a transonic drag reduction technique will be evaluated. Infrared flow imaging will be used to qualitatively evaluate the nozzle/afterbody and external burning plumes interaction with the tunnel flowfield. Heat transfer, temperature, and static pressure will be measured as well as force.

Comparison of Hot and Cold Pressure Distributions



Ramp surface pressure distribution

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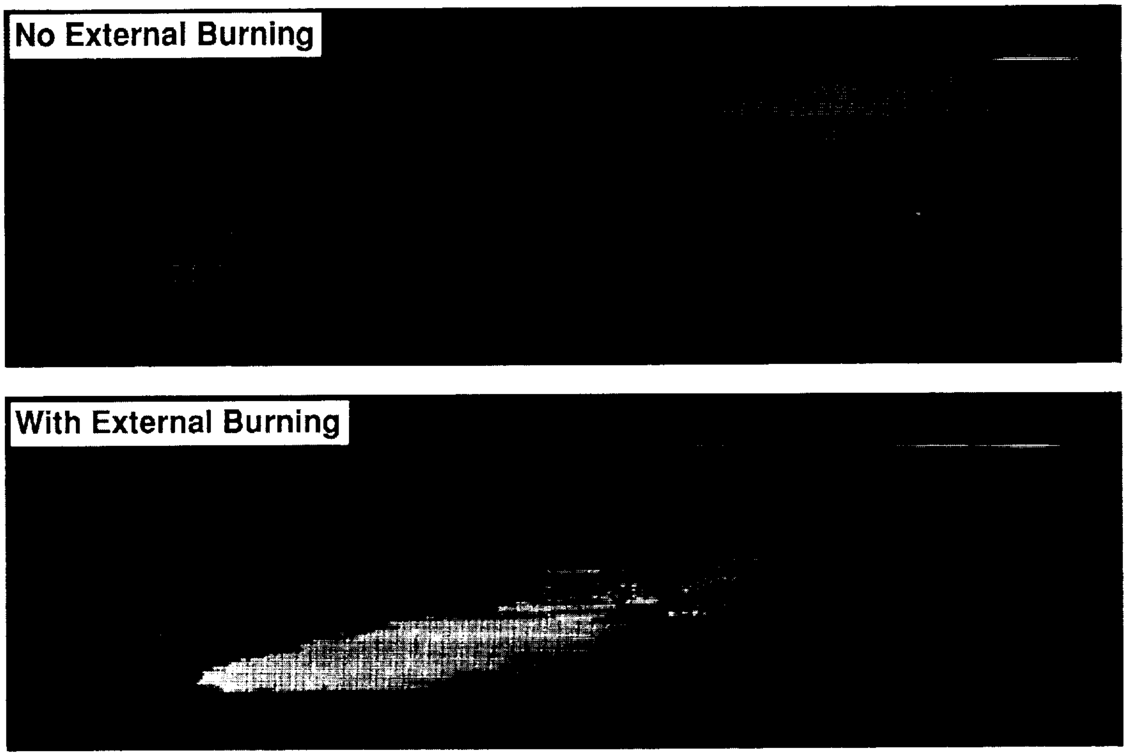
NASP nozzle testing to date at NASA's Langley and Lewis Research Centers has been conducted with cold air as the test medium. Questions naturally arise as to the scaling of this data to flight conditions, where hydrogen-air combustion products comprise the working fluid. Using the Jet-Exit Rig, the first NASP nozzle performance data using realistic combustion products is being obtained. Shown in this figure is a comparison between cold data taken at the Langley 16-Foot Transonic Wind Tunnel, and hot data taken recently in the Lewis 8- by 6-Foot Supersonic Wind Tunnel with the Jet-Exit Rig. The centerline pressure distributions shown look qualitatively similar, with some subtle differences near the cowl trailing edge. The implications of these subtle differences are currently being assessed.

Jet–Exit Rig External Burning Capability

Infrared Images



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External burning as a means to reduce transonic nozzle drag is currently being investigated. Infrared images taken during a recent test show the Jet-Exit Rig in operation with and without external burning. The external burning hydrogen fuel is injected through a row of sonic orifices just upstream of the cowl trailing edge at pressures from 50 to 1000 psia. Ignition of the external burning stream is accomplished by the 3000 °R main exhaust flow.

Summary

- NASP nozzle is highly overexpanded at transonic conditions
- Experimental and computational work is underway to
  - Characterize performance of candidate geometries
  - Reduce transonic drag to manageable levels
- Performance data with hydrogen combustor are being taken
- External burning shows promise as a drag-reduction technique

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